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Measurements and Analysis of the Epidaurus Ancient Theatre Acoustics

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Dedicated to the memory of Stamatis Vassilantonopoulos (1947–2010)

Summary

Extensive results are presented for acoustic and meteorological measurements at the ancient open theatre of Epidaurus. The analysis of the results, illustrates most aspects of the theatre's acoustic properties, indicating the pattern and mechanism for the early reflections, the spectral response of the theatre, aspects of time-frequency response interaction and aspects of the spatial impression. The results also verify predictions of earlier acoustic models for this theatre and indicate no significant effects from environmental factors such as temperature, humidity and wind variations across the theatre. Measurements with the theatre partially full with audience show no change with respect to speech intelligibility. The results restate the renowned exceptional acoustic characteristics of the theatre for speech, for all listener positions.

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1. Introduction

The evolution of the classical-era theatre architecture from the 6th century BC to the beginning of the Hellenistic period in the 4th century, an age that saw the flourishing of mathematics and acoustics via the influence of Pythagorean science, led to amphitheatres with improved acoustics and visibility and culminates with the theatre of Epidaurus. The theatre is located at the eastern Peloponnese and was constructed in the sanctuary of Asclepius, the god of health and medicine, noting also that the ancient Greeks' interest in the voice, speech, music and acoustics is based upon their theory of sound as a cathartic force. The name "Epidaurus" is etymologically related to "ἐπι τῇ ἀύρᾳ", indicating a place either affecting the human aura, or been affected by the wind. Today it represents the best preserved of the classical Greek theatres and its remarkable acoustics with renowned speech intelligibility for audiences up to 14500 people, raise the interest both of experts and visitors. The theatre is functional, hosting mainly theatrical acts during the summer months.

For a long time, acousticians have discussed and examined the theatre's properties [1, 2], but in the past, mainly due to equipment limitations, the acoustic measurements of the theatre [3] did not fully explain the reasons for such

acoustic performance. A detailed computer acoustic simulation of the theatre was performed by Vassilantonopoulos and Mourjopoulos in 2002 [4], which predicted high speech intelligibility and described the paths for the theatre's early reflections. These results were confirmed in 2004 by detailed measurements for the same source-receiver positions [5, 6]. The measurements also revealed a frequency response dominated by a dip at approximately 180 Hz and an amplification of the 500–1500 Hz region. Note that the good correlation between ancient theatre computer modelling and measurements was also discussed in [7].

To analyse the theatre's acoustics, Declercq and Dekeyser [8] employed a geometric-based acoustic modelling method incorporating multiple orders of diffraction and concluded that the backscattered sound from the cavea amplifies high frequencies (above 500 Hz) more than low frequencies, thus proposing this as reason for the high speech intelligibility. Given the importance of the reflection patterns in open-air theatres –but not specifically for Epidaurus– Farnetani *et al.* [9] studied such effects with measurements both in-situ and in scale models, also indicating the importance of the direct sound, the two early reflections from the floor and stage building (when present) and reflections that correspond exactly to seven step edges behind the microphone position. Following this, the effect of the ground floor and cavea tier steps specular reflections and edge diffraction was also studied in [10]. Lokki *et al.* [11] developed a model of the lower cavea of the Epidau-

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rus via a 3D finite-difference time domain (FDTD) method and a beam tracing method. They illustrated the theatre's sound field evolution and found that the direct sound and floor reflection from the stage floor are integrated together at low frequencies and are combined with the backscattering from the seat rows behind the receiver positions, thus confirming the predictions from earlier studies [9]. They have also shown that the interference of this backscattered sound is responsible for the 180Hz dip in the theatre's frequency response, their predictions being in good accordance with the measurements [5, 6]. Furthermore, they predicted sufficient level for the 100Hz response region and wideband amplification of frequencies above 500Hz. They concluded that the high speech intelligibility and strong sound of the Epidaurus theatre is due to the integration of the direct sound, the floor reflection, and the forward and backscattering of the seating area.

Subsequently other authors have also measured the theatre [12, 13], their results largely confirming the earlier measurements for the range of the theatre's acoustic parameters; however, the extensive and lengthy measurements of Psarras and Kountouras in 2011 [14] have provided novel findings especially with respect to the effect of audience on the theatre acoustics. Their results are combined here with the 2004 measurements of Vasilantonopoulos and al. [5, 6]. This full measurement set is analysed here and illustrates clearly the dominant acoustic mechanisms and the contribution of the reflection components with respect to the acoustic parameters and especially speech intelligibility. Hence this work can verify predictions of the previously discussed models and give clearer reasons for the theater's renowned acoustics. The frequency and spatial domain properties are also discussed and the results are presented for multiple receiver positions and over different and lengthy observation intervals. Detailed meteorological data are also examined for the potential contribution of such environmental factors. Finally, novel results of the acoustic parameters are provided for intervals when the theatre was progressively occupied by audience during ancient drama performance.

2. Measurement methodology

The measurements of the theatre were performed on 2 different periods, in each case by different research groups:

- i) acoustic measurements indexed as M1 were performed on 8/4/2004 during 13:00 – 15:00 hours on a cloudy day with air temperature of approximately 22 °C, by a research groups from the University of Patras (UoP) at an unoccupied theatre [5, 6] (Figure 2a). The measurement positions (shown in Figure 1), were chosen at exact locations and distances employed during an earlier computer simulation study of the theatre to assist identification of sound reflection paths [4]. The sound source was a self-powered studio monitor loudspeaker placed at a height of 1.5 m, in the centre of the stage ("orchestra", position S1). Some measurements were also obtained for the position S2, approximately 5 m from S1,

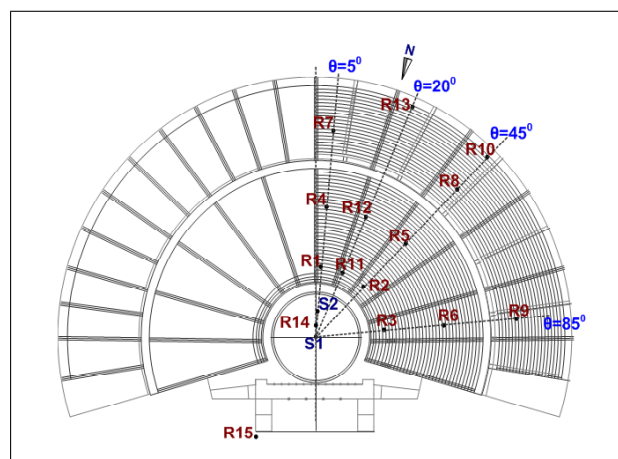


Figure 1. Plan view of the theatre with tested source (S1, S2) and receiver (Rx) positions.

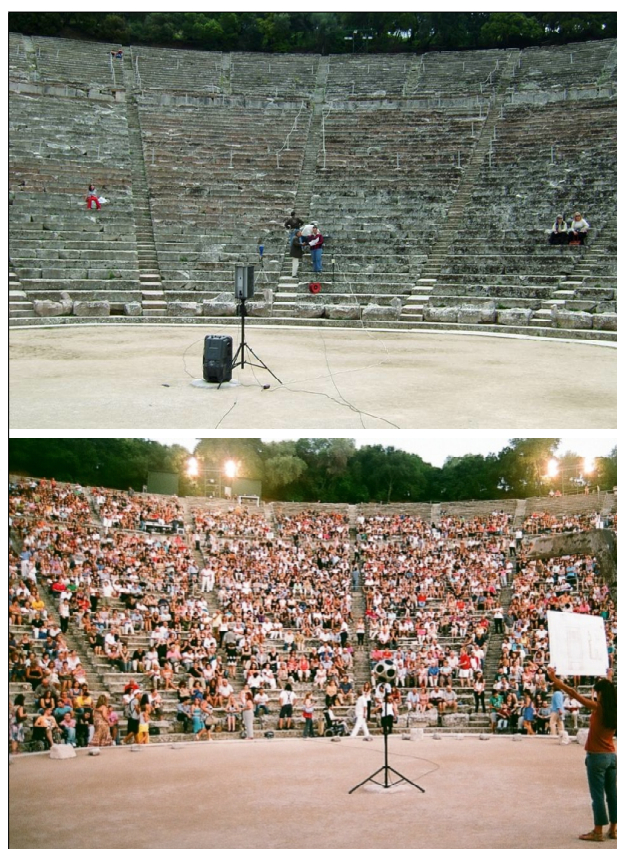


Figure 2. acoustic measurements (a) for set M1 unoccupied theatre, April 2004; (b) for set M2B, theatre with audience, July 2011.

towards the audience (see Figure 1). The excitation signal (both MLS and sinusoidal sweep) was measured at 105 dB SPL/1m at position R14, (Figure 1) while the background noise was approximately 55 dB (40 dBA). Note, that during these measurements and also during those for set M2 (described below), no interference from traffic noise was observed. However, other noises were often present in a time-varying and unpredictable fashion: noise from crickets was present during warm

Table I. Measurement type, index, date and receiver positions. M1: measurements during April 28th, 2004, by the UoP team. M2A: measurements during June 15–17th, 2011, by the AcH team. M2B: measurements during June 22–23rd, 2011, by the AcH team. O: omni receiver; B: dummy head receiver; L: sound pressure level meter, S: simulations [4]. W: weather station (at height 2 m), W': weather station (at height 7 m). R16: walkthrough R17: hemisphere.

Index	Receiver positions		Acoustic measurements				Meteo measurements	
	Distance r [m]	Angle θ [deg]	M1	M2A	M2B audience		M2A	M2B
					no	yes		
R1	15.63/10.63	5	O, L, S	B, L	B	-	-	-
R2	15.63/10.63	45	O, L, S	B, L	B	-	-	-
R3	15.63/10.63	85	O, L, S	B, L	B	-	-	-
R4	29.42	5	O, L, S	B, L	B	O, B, L	-	-
R5	29.42	45	O, L, S	B	B	-	-	-
R6	29.42	85	O, L, S	B	B	-	-	-
R7	47.59	5	O, L, S	B	B	-	-	-
R8	47.59	45	O, L, S	B	B	L	-	-
R9	47.59	85	O, L, S	B	B	-	-	-
R10	57.60	45	O, L, S	B	B	-	-	-
R11	15.63	20	-	O, L	-	O	-	-
R12	31.75	20	-	O, L	-	O	-	-
R13	57.60	20	-	O, L	O	-	W	-
R14	1	0	L	L	L	-	W, W'	W
R15	20	185	-	-	-	-	W	-
R16	57.6–1	~5	-	L	-	-	-	-
R17	15	n/a	-	O	-	-	W	-

days and occasional noise activity from visitors or wind was producing peak noise levels up to 47 dBA. Nevertheless, as was also found by Barkas and Vardaxis [15], Epidaurus remains one of the quietest ancient theatres in Greece, having an average background noise of 39 dBA. From the measured responses, the on-axis anechoic impulse response of the source loudspeaker was deconvolved, so that subsequently analysed responses could be free of any (on-axis) time-frequency domain signature due to the source excitation. This would especially assist in the clear identification of the theatre's reflection patterns. The measurement set can be freely downloaded from [16].

- ii) acoustic and meteorological measurements indexed as M2 were performed by a research group from Athens and Thessaloniki (AcH), during June and July 2011, on two phases [14]. From 15 until 17/6/2011 measurement set M2A was obtained under unstable weather conditions (ranging from sunny to cloudy and rainfall periods) and low temperatures for summer season at the unoccupied theatre. The acoustic data were obtained mostly for dry ground surfaces. From 22 until 23/7/2011 (with sunny weather and normal temperatures for the period) measurement set M2B was obtained which also included data both for an unoccupied state but also for the theatre progressively occupied with audience of approximately 300 up to 3500 people, prior to a theatrical ancient drama performance of Medea (Figure 2b). Note that as is customary during performances, the lower tiers were covered by plastic cushions and the orchestra ground was watered. For

both M2 sets, measurement positions were to a large extent similar to those of set M1, but further receiver positions were added (see Table I and Figure 1). The sound source was a dodecahedron loudspeaker at position S1 and at 1.7 m height, generating up to 105 dBA ($L_{Aeq,10sec}/1$ m) at R14 using 11 and 20 sec log sweep and pink noise. In addition to single channel omni microphone measurements which were also taken at multiple time intervals, dummy head (binaural) measurements were also obtained at the same R1–R10 positions as for set M1. Single channel measurements were also taken at $r = 1$ m from S1 at 900 intervals at a hemisphere in the x/z plane (R17, Table I). To minimise audience annoyance during the occupied M2B set, limited range of measurements were possible. Table II describes the equipment employed during all measurements.

3. Results for the meteorological parameters

Given that systematic atmospheric variations in the theatre may affect wave propagation and sound transmission, and to evaluate speculations in the literature concerning their effect [8], meteorological measurement were taken by three portable weather stations at positions R13, R14, R15 and R17 (see Figure 1 and Tables I, II). These stations were logging continuously one minute averages, max and min of the following parameters: air temperature, humidity, wind velocity and direction, placed at specific positions at different elevation points. These were taken during set M2A (not shown) and set M2B starting on 22/07/2011

Table II. equipment type and quantity employed for the theatre measurements.

Measurements	Equipment type	Date/Index
sources	1xATC SMC 20-2 Active Monitor	2004 / M1
	1xBrüel&Kjær Type 4292 OmniPower Sound Source	2011 / M2A,B
	1xBrüel&Kjær Type 2716 Power Amplifier	2011 / M2A,B
microphones	1xACO Pacific , 1 x Probe Norsonic 1234	2004 / M1
	1xBrüel&Kjær Type 4952 Outdoor microphone	2004 / M1
	1xIntensity Probe Norsonic 240	2011 / M2A,B
	2xBrüel&Kjær Type 4952 Outdoor microphone	2011 / M2A,B
	2 x Brüel&Kjær UA-1404 Outdoor microphone kit	2011 / M2A,B
	1xBrüel&Kjær Type 4100 Head and Torso Simulator	2011 / M2A,B
	1xBrüel&Kjær Type 4101 Binaural microphone	2004 / M1
sound analysers –	3xBrüel&Kjær Hand-held Analyzer Type 2270-E incl. BZ-7225 Enhanced Logging software and BZ-7226 Sound Recording Option	2011 / M2A,B
sound level meters	1xBrüel&Kjær Hand-held Analyzer Type 2250-E incl. BZ-7225 Enhanced Logging software and BZ-7226 Sound Recording Option	2011 / M2A,B
software	1xWinMLS	2004 / M1
	1xBrüel&Kjær Type 7841 Dirac software	2004 / M1
	1xBrüel&Kjær Type 7841 Dirac software	2011 / M2A,B
computer audio interfaces	1xRME Fireface 800 8ch I/O Firewire	2004 / M1
	1xTascam US 122	2004 / M1
	1xMOTU Traveler 8ch I/O Firewire	2011 / M2A,B
calibrators	2xBrüel&Kjær Type 4231 Sound calibrator	2011 / M2A,B
accessories	Brüel&KjærType 3535-A All-weather case, 1xmast, 1x<7m tripod, 4x<1,5m tripod	2011 / M2A,B
weather stations	3xDavis Vantage Vue Weather Station Sensor Suite 1xDavis Envoy8x Data Logger	2011 / M2A,B
distance meter	2xLeica Disto Laser Distance Meter	2011 / M2A,B

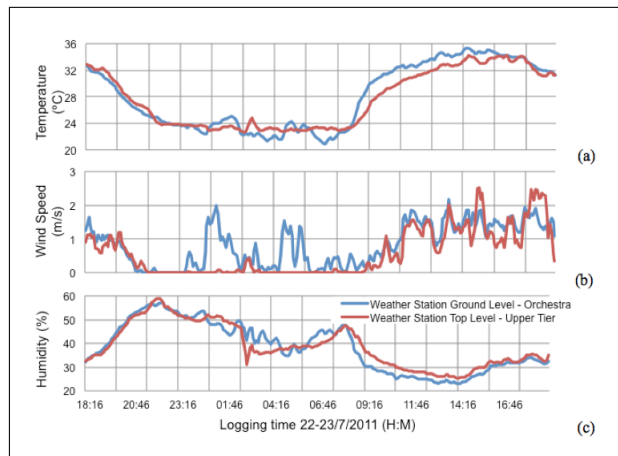


Figure 3. smoothed results for (a) Temperature, (b) Wind speed and (c) Humidity for the M2B set. Note that elevation difference between two weather stations was approximately 20 m; Wind direction was NE to N (from the top of tier, Figure 2).

at 18:16 until 23/07/2011 at 19:07 (Figure 3). Given a vertical temperature gradient as in Figure 3a, sound waves may propagate on curved paths with radius of curvature $R(m)$ (see Appendix A1). For the evening periods (Figure 3a) temperature and consequently the speed of sound increases with the height, hence the sound waves are refracted downwards. However, during the daytime peri-

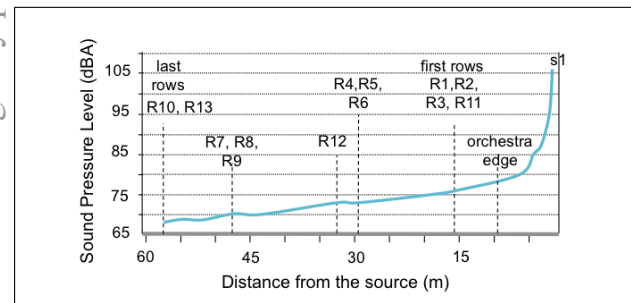


Figure 4. Sound pressure level variation from a 105 dBA omnidirectional source at position S1.

ods (e.g. 08.30–16.40), temperature gradient and speed of sound was decreasing with height, causing the sound waves from the source to be refracted upwards. Nevertheless, calculations (see Appendix A1) indicate here a large radius of wave curvature $R(m)$, exceeding the dimensions of the theatre, so that no part of the theater was located within the predicted shadow zone. However, the temperature gradient was also significant between the individual components of the theatre (see Figure 15).

Considering now the combined effect of humidity and temperature gradient, Figures 3a,c show that for a typical summer day during the morning (08–14h) the temperature varies from 28 to 34 °C and the relative humidity from 25 to 40% , whereas during the evening–night times (18–23h)

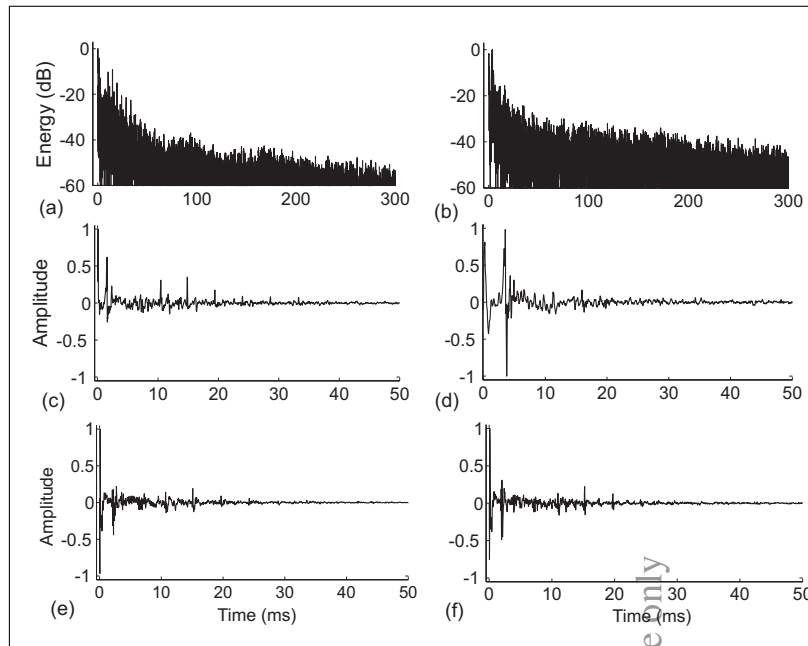


Figure 5. impulse response normalized energy in dB for the source in S1 and for the receivers positions R1, (a) and R8, (b); early impulse response part for positions R1, (c) and R8, (d) for source in S1; early impulse response part for source in S2 and for receiver positions R1, (e) and R2, (f). The responses are obtained after deconvolution by the on-axis anechoic response of the loudspeaker, hence corresponding to delta function excitation.

the range is between 24–32 °C and 30–60%. By reference to look-up tables [17] the above variations suggest an additional level attenuation ranging from 0.5 dB/100 m up to a maximum of 3 dB/100 m for the frequency range of 1–4 kHz. Clearly over the maximum distance of 57.6 m, such an effect must be less than 2 dB. Considering now the effect of wind, its speed during a typical summer day appears to vary from 0 to 2.5 m/s; for a direction towards the audience and for a positive temperature gradient with height, the sound waves may be refracted downwards, resulting to an increase of sound pressure level at the upper seat rows. Figure 3b shows that the wind speed is gradient is significant during the night but it is fluctuating during the daytime, so no safe conclusion can be drawn. Furthermore, during the measurements, wind direction was N to NE, i.e. from the upper rows towards the stage, so again such an effect could not contribute to sound amplification at the distant positions. Hence, no systematic or significant influence of the above factors could be identified and any further acoustic results must be mostly attributed to the theatre's geometric design.

4. Results for the acoustic parameters

4.1. Sound pressure level

Figure 4 indicates an approximately 36 dB level difference between an omni source at the centre of stage S1 and the more distant listening position. Given that for the unoccupied theatre the noise level was approximately 40 dBA, it is clear that for such positions, signal to noise ratio (SNR) is low and hence speech intelligibility can be critical being affected by the level of the actor's voice and the background/audience noise levels. The results indicate nearly a 6 dB per distance doubling level drop within the orchestra region, typical of the free field radiation. However as

the receiver moves up to the cavea, the level drops at approximately 3 dB per distance doubling, indicating a semi-reverberant field. This may be also attributed to the dominance of cylindrical wave backscattered from the upper tiers. There is approximately 6 dB difference in level between the extremes in audience positions.

4.2. Time domain composition of sound field

The sound field of the theatre is formed by an early reflection from the orchestra floor, specular reflections from the cavea steps and diffracted sound energy. This reflected energy decays fairly shortly, approximately after 200 ms to the noise floor level (see Figure 5a,b), although for the distant positions this SNR range is reduced by approximately 6 dB (see also previous section). These plots reveal a 40 dB decay within approximately 60 ms from the direct signal arrival (see Figure 5). Hence, the theatre's sound reflection and diffraction pattern contributes to early arriving energy that mostly due to the precedence effect generated by the first reflections (see below), is perceptually integrated with the direct source signal [18]. Clearly, this property more than anything else will contribute to high speech intelligibility, since listeners perceive an amplified signal level originating from the source position.

Observing now more closely the early parts of impulse responses in Figure 5c and 5d (for the source S1) and in Figure 5e and 5f (for the source at S2) and also via the computer simulations for the same positions [4], the following conclusions can be drawn: for close positions (e.g. R1, R2, R3) the first reflection arrives approximately 1.7 ms after the direct signal and is generated from the stage floor. A second pattern of reflections arrives at about 6 ms and comes from the listener's front aisles. A different mechanism is observed for the distant positions (e.g. R7, R8, R9): the first reflection system arrives at 1.3 ms, generated by the front seating aisles; the second reflection ar-

rives approximately at 3.5–4 ms and is from the floor of the orchestra. These closely arriving early reflections (within an interval of less than 5 ms) are combined to generate energy higher than the direct signal component, practically enhancing its perceived level.

Beyond 10 ms, for the lower cavea positions, a distinct specular reflection pattern can be observed (more clearly in Figure 5c), resembling a comb filter response, generated by backscattered periodic reflections from the seating steps above the listener. Six or seven such decaying reflections of the source signal can be clearly observed, arriving at approximately 5 ms intervals having well-preserved sharp attack, followed by second order reflection of the stage floor reflection pattern hence confirming earlier model predictions [9]. At later intervals, multiple order reflections arrive from more complex paths including the sides of the cavea.

Nevertheless, scattered reflections are also arriving from forward positions in the front aisles, having less sharp onset pattern and being at approximately 10 dB lower in level than the backscattered specular reflections. This is the dominant reflection mechanism for the upper cavea positions (see Figure 5b,d) especially for the last upper row where there are no seating rows to the back. Significantly, for such distant positions scattered and specular early reflections seem to focus after the direct signal arrival and generate useful to speech intelligibility energy. With respect now to the responses due to the closer source position S2, shown in Figure 5e (for receiver at R1) and Figure 5f (for receiver at R2), a similar reflection mechanism is observed as was described for the case of source at S1 (e.g. Figure 5c). Note that the polarity of reflection from the stage floor is now reversed and all specular reflections have even sharper attack profiles, indicating a higher degree of high frequency content reaching this nearer to the source position given the radiation pattern from the source (this is confirmed also by the Figure 6a). For the same reason, all low level diffuse reflection energy components appear to have higher frequency content.

4.3. Frequency domain composition of sound field

The acoustics of theatre impose a characteristic filtering to the frequencies of sound signals. As is shown in Figures 6a,b for the source at the centre of the stage, the frequency response is characterized by a significant dip at 170–200 Hz, a broad amplification region around 1000 Hz for the close receiver positions with additional peaks appearing at 300 and 1500 Hz, for the distant positions. At the same time, for all receiver positions the low frequency region of 80–150 Hz, close to male speech pitch (85–155 Hz), is also transmitted with sufficient amplitude and volume. The results confirm the model predictions of Lokki *et al.* [11], indicating that the theatre's step size (height 0.367 m) and distinct backscattered reflection pattern (see previous section) generate the interference dip, whereas energy from the seating top (width 0.746 m) and the stage floor mostly contribute to the amplification regions, especially the male speech preserving 100 Hz re-

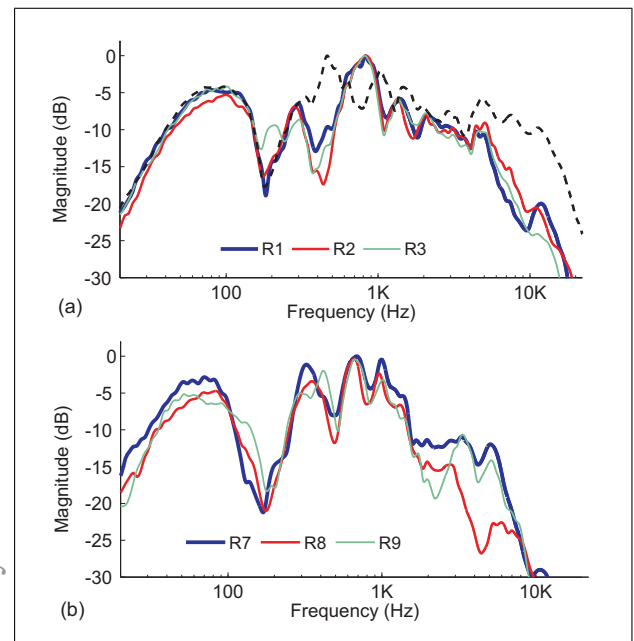


Figure 6. Normalised magnitude frequency response of the theatre at: (a) close positions / different angles and (b) distant positions / different angles. Note that low frequency roll-off is dictated by the loudspeaker response. All solid lines are for source position at S1. Dotted line in (a), shows response at R1, for source position at S2.

gion and the significant to intelligibility 1000 Hz region. The measurements also confirm the amplification above 500 Hz predicted by the Declercq and Dekeyser model [8], although not their predictions for low frequency attenuation.

Furthermore, their explanation for the high intelligibility of the theatre due to such spectral properties alone can be only partially validated, given that the time domain response properties discussed earlier illustrate more clearly the perceptually-compliant mechanisms for this. These authors also predict that the Epidaurus theatre has a specific spectral profile due to its specific “seat row periodicity” and this may be different to other ancient theatres, where this amplification region is shifted due to different cavea geometry and seat row periodicity. For given source position, the broad form of the spectral response does not change drastically with either the receiver position or angle (Figure 6). However, when the source is moved to the front of the orchestra (near the first aisles for the source at S2, as is shown by the dotted line in Figure 6a), then it was observed that the resonance region is shifted towards lower frequencies. Furthermore, as is expected for this closer to the receiver position and the radiation pattern of the source, a larger amount of high frequency signal (especially above 5 kHz) is reaching the receiver. These largely invariant with the position response characteristics can benefit transmitted speech signals, preserving well the male speech pitch and formant regions.

Considering the time-frequency response of the theatre (Figure 7), it is obvious that the mechanism of the early reflections from the floor of the orchestra and from scat-

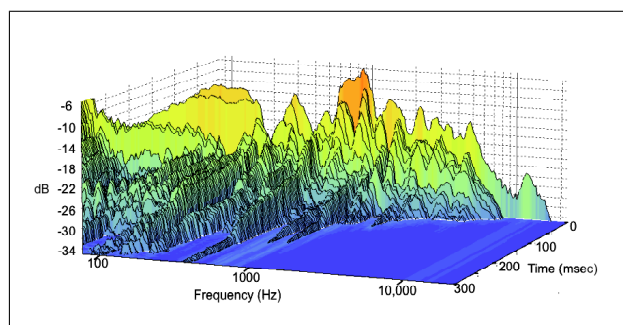


Figure 7. Time-frequency analysis of the response for receiver position R1.

tered energy from the seat rows as was mentioned above and in [11], is responsible for the characteristic spectral amplification effect which provides useful to intelligibility energy for the early time intervals (e.g. up to 60 ms) reinforcing the direct sound. Late low level reflection energy decays for up to 150-200 ms, while for subsequent intervals, the dense diffuse and higher order reflections, generate a flatter spectrum. Figure 7 also shows an –additive to the response– largely subsonic component below the region of excitation, (e.g. 10 Hz), which builds up beyond 100ms. This was measured even when wind speed was extremely low (0.1 m/s), so a further investigation of this effect must be undertaken.

4.4. Acoustic parameters (D50, C80, STI, RASTI, T30, G)

Figure 8 presents the acoustic indices measured for various distances and angles for source at S1. Considering the Definition D50 (Figure 8a) and Clarity C80 (Figure 8b) it can be observed that the performance is very good, regardless of the source-receiver distance, being lower only for the side receiver position. Similarly, excellent is the measured intelligibility of speech via RASTI and STI (Figure 8c), which is above 0.8 and independent of distance, only being slightly reduced for the distant side position. Results for source at position S2, illustrate identical performance (for the limited receiver positions tested). The results confirm the exceptional speech clarity in this theatre mainly due to the previously discussed contribution of the early reflection response energy.

Note that the results from measurement sets M1 and M2 were taken 7 years apart and still are consistent with time. Figure 9a gives 2-day average results from set M2A for RASTI and STI, also shown the same consistent high intelligibility values apart for the distant position R13 which may be more susceptible to occurring interfering noise.. Given the unpredictable and random nature of noise interference (as was discussed in Section 2), the effect of varying noise in the estimated STI values was also evaluated for the measured response set M1, by assuming noise interference conforming to NR35 profile. These RASTI and STI values are shown in Figure 9b and also indicate that especially for the more distant positions, speech intelligibility may be reduced, nevertheless remaining above 0.8.

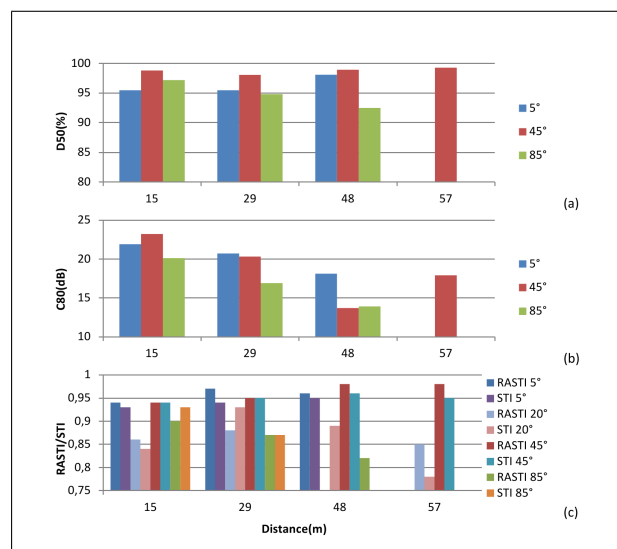


Figure 8. (a) Definition D50, (b) Clarity C80 and (c) Speech Intelligibility RASTI, as function of receiver distance and angle (for source at S1) and for unoccupied theatre.

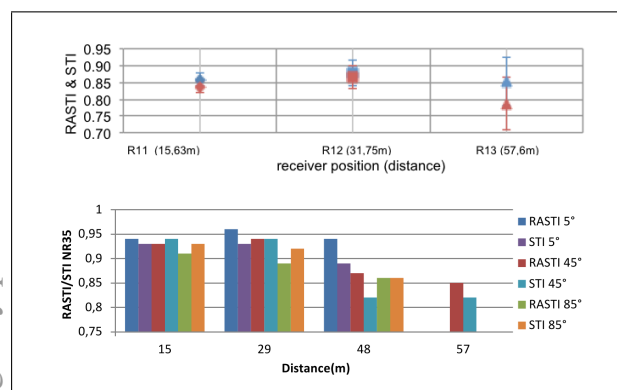


Figure 9. (a) Two-day average results for set M2A and positions R11, R12 and R13, for RASTI (blue) and STI (red). (b) RASTI and STI results for set M1, assuming a NR35 noise curve.

Some similar factors may result to small variations in measured parameters, as can be seen in [12, 13]. Figure 10 shows also the frequency dependence of these parameters over 2-days. It was found that C80 (see Figure 10a) and D50 (not shown) were high especially for the amplified region above 500 Hz.

The Strength G parameter was also found to increase around 500 Hz (see Figure 10b), but overall was low for position R13.

Binaural impulse responses were obtained via dummy head and the results in Figure 11 for Inter-aural cross-correlation (IACC) indicate high degree of spaciousness in the theatre sound field. As was also found in [4, 6], lateral reflections appear to reach listeners with progressively sharper angles, for increasing the distance from the source, leading to a drop of the lateral energy LEF for distant positions.

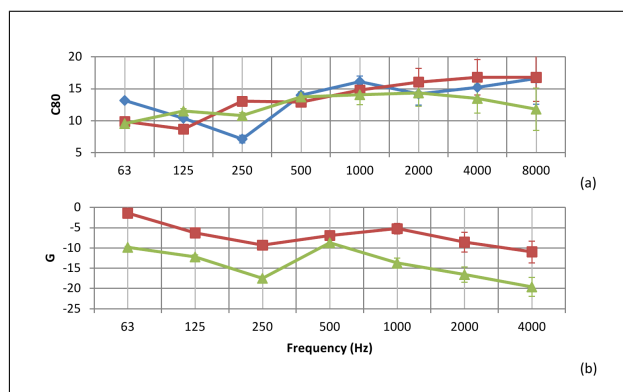


Figure 10. Two-day average results for set M2A; (a) Clarity C80, and (b) Strength G, as function of frequency for receiver position R11 (blue), R12 (red) and R13 (green) for an omni source at S1.

4.5. Effect of the audience

Although Reverberation Time parameters are not in principle applicable to open space acoustics such as for the Epidaurus theatre, it is useful to relate to such parameters in order to obtain some rough indication of the space's overall absorption to sounds. Here, novel results reveal some mild reduction in the T30 parameter (Figure 12) when the theatre was occupied by an audience of approximately 3000 people (approximately 1/4 of its full capacity). It is evident that the additional absorption has marginally reduced the reflection energy from seating row surfaces.

Significantly, binaural spaciousness was significantly reduced as the theatre was filled with audience (see Figure 13), indicating that late, low level lateral energy from the cavea is progressively reduced at higher frequencies due to increasing audience absorption.

Speech Intelligibility indices measured on June 22–23rd 2011 set M2B) with progressively increasing audience reveal interesting results (see Figure 14). RASTI and STI values with audience were found to be largely similar to those for the empty theatre measured on June 15–17th 2011, (set M2A, see Figure 9). However, for the M2B set, STI was found to be significantly lower for the empty theatre than for the case with audience, especially at R12 (middle of cavea). When the theatre was progressively filled with audience, these values were found to be as for the typical earlier measurements of the empty theatre (sets M1, M2A). An explanation of this is that for the M2B set, prior to the theatrical ancient drama performance of Medea, plastic cushions were laid on top of the lower cavea seating rows. Given the discussed beneficial contribution of forward scattered reflection energy from seating top surfaces for enhancing the early response of the theatre, it appears that these cushions had significantly reduced this beneficial effect and affected more its performance when they were not occupied by audience. Nevertheless the speech intelligibility for the theatre with audience was found to be similar to that measured for its typical empty state.

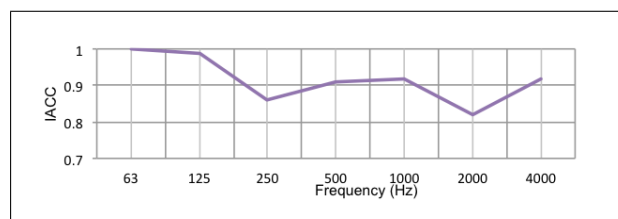


Figure 11. Interaural cross correlation (IACC) as function of frequency for position R11.

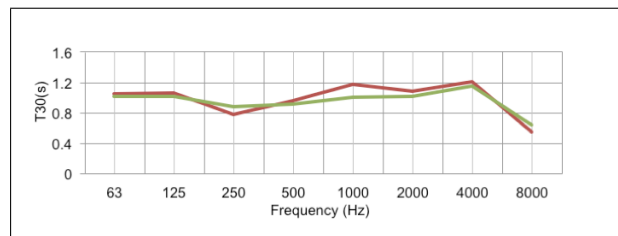


Figure 12. T30 as function of frequency for empty (red) and occupied (green) theatre for position R12.

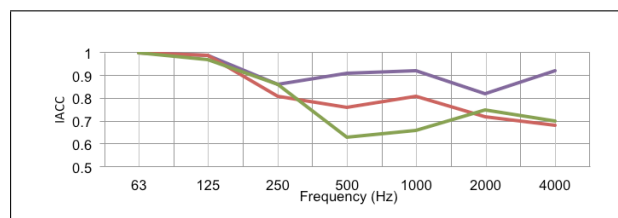


Figure 13. IACC as function of frequency for empty (blue) and occupied theatre (red: 300 attendants, green: 3000 attendants) for position R12.

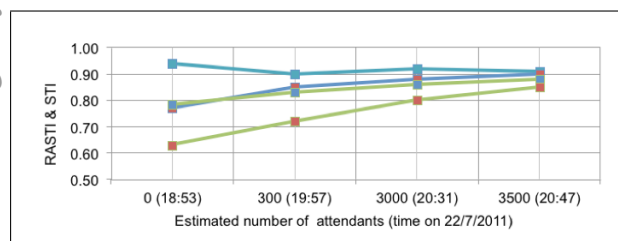


Figure 14. Speech Indices RASTI and STI as function of audience occupancy, for positions R11 (blue lines, blue dots: RASTI, red dots: STI) and R12 (green lines, blue dots: RASTI, red dots: STI). Note that during the measurement set M2B, seating cushions were laid at lower tier level rows.

5. Discussion and conclusions

No significant influence of environmental factors for the theatre's acoustics was detected by the analysis of the meteorological data. Results for the temperature gradient between the orchestra and the upper seating rows indicate a sound pressure amplification or attenuation radius far greater than the theatre size and hence this parameter as well as the measured humidity fluctuations cannot significantly affect sound transmission to listeners. Effects due to wind are inconclusive, but they indicate minimal contribution to sound propagation. Hence, the acoustic properties

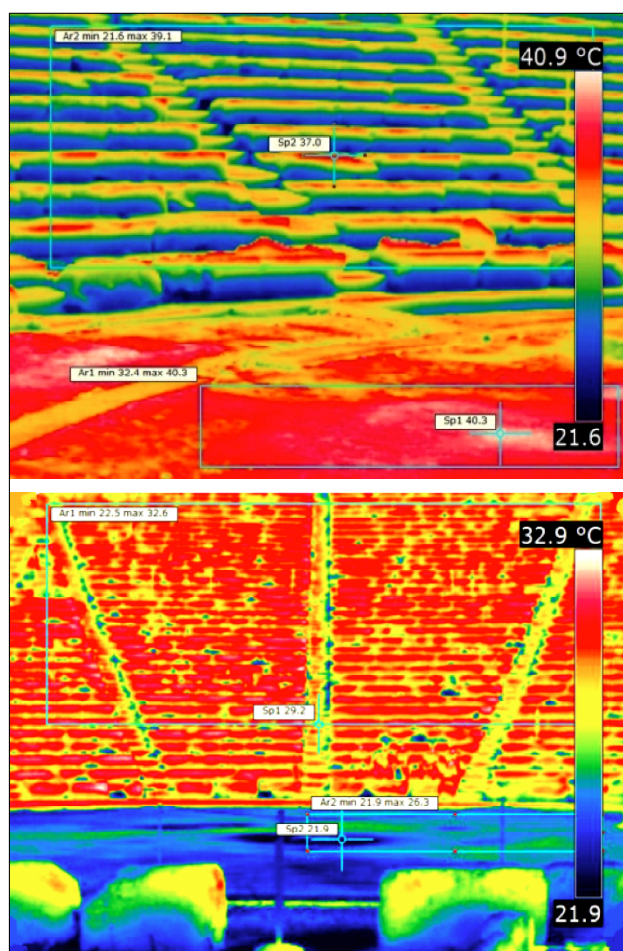


Figure 15. set M2A thermal camera images; (a) 13.00 hours, orchestra temperatures between 32.4 °C and 40.9 °C, cavea temperatures between 21.6 °C and 39.1 °C. (b) 19.00 hours, orchestra temperatures between 21.9 °C and 26.3 °C, cavea temperatures between 22.5 °C and 32.6 °C.

are mostly a result of the theatre's shape, geometry and reflecting surfaces.

In the cavea, there is approximately 6 dB difference in source signal level between extreme audience positions, there is a 3 dB drop per distance doubling and the sound pressure level is dropping by approximately 36 dB up to the upper rows from an omni source at centre of stage. Hence ambient or audience noise can greatly affect speech intelligibility for such critically low SNRs at the distant positions.

The theatre impulse responses show a 40 dB decay within approximately 60 ms after the direct signal arrival. Hence, the theatre's design contributes to large amount of early reflected energy that for such intervals is known to be perceptually integrated and enhancing the direct source signal. It is well known that in such cases the listeners perceive an amplified signal level originating from the source position, hence assisting speech intelligibility. Some low level reflection energy decays for up to 200 ms after excitation, providing mainly spatial envelopment, but especially for the distant positions, such reflected energy can be practically covered by the noise floor.

The detailed paths for the generation of such beneficial to intelligibility reflections were traced with the aid of a previous computer simulation study [4] and the observations largely confirm earlier model predictions [8]. Apart from the stage floor reflection that arrives very shortly after the direct signal, there are periodic specular reflections mostly from the back of the seats above the listener as well as reflection patterns from forward to the listener upper tier surfaces. For the upper row positions, the floor reflection arrives shortly after the first forward aisle reflection, so that the combined strong reflection pattern at approximately 5 ms reinforces the direct signal.

The frequency response is characterized by a strong dip at 170-200 Hz, a broad amplification region around 1000 Hz and sufficiently amplified level for the low frequency region of 80-150 Hz, close to male speech pitch frequency. This confirms the model predictions of Lokki *et al.* [11], indicating that the distinct backscattered reflection pattern dictated by the theatre's step size generates the interference dip at around 180 Hz, whereas spectral amplification regions are also derived from the seating upper surfaces and the stage floor reflection. The reinforced broad region around 1000 Hz is largely decaying within 40 ms, hence benefiting speech intelligibility; low level energy especially at low and subsonic frequencies decays for longer time intervals. Further investigation must confirm the nature and properties of such response components.

The measured results for the acoustic parameter and speech indices confirm the exceptional speech clarity in this theatre. The intelligibility of speech via RASTI and STI was above 0.8 only being slightly reduced for the distant and side listener position; for most positions this performance was found to be consistent over time.

Clarity C80 and Definition D50 parameters were also found to be very good, especially around the spectrally amplified region, whereas T30 was measured around 1 sec. Similarly perceived spaciousness via the IACC was found to be exceptional for the empty theatre.

Significantly, novel measurement results during a progressively filled with audience theatre (approximately up to 1/4 full capacity), reveal that T30 was not drastically reduced. In contrast, IACC was progressively reduced with audience size, especially above 250 Hz, indicating the reduced contribution of late, multiple order reflections and diffuse energy from the cavea sides. RASTI and STI measurements indicate that with partially full of audience, these parameters were comparable to those measured at previous dates for the empty theatre. However, for that particular measurement date, the results for the unoccupied theatre were found to be lower possibly due to the absorption introduced by the specially laid plastic cushions over the tops of lower tier seats. This illustrates the significance of the reflected energy from these seating surfaces for speech intelligibility at higher positions in the cavea.

The measurements and results presented here clarify sufficiently the mechanisms and reasons for the theatre's acoustic properties. The results also confirm some of earlier model predictions and also support the the-

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atre's renowned reputation for speech reproduction, being largely invariant over time, listening position, and up to the measured degree, consistent even when audience was present. Given that no systematic contribution from environmental factors was detected, the good results for speech intelligibility and other acoustic indices must be attributed to the specific theatre geometry and surface properties. It is of interest to further investigate if the exemplary design of this theatre was a result of conscious choices, empirical knowledge, evolution procedure or other factors.

Appendix

A1. Evaluation of temperature effect on sound propagation

As it is known [17], the principal meteorological conditions that affect sound propagation are the wind distribution and the vertical temperature gradient. Due to vertical temperature gradient any sound wave traveling nominally parallel to the ground will have a curved path with radius of curvature $R(m)$ defined as

$$R = \frac{c_0}{dc/dh},$$

where c_0 [m/s] is the speed of sound, dc/dh [1/s] is the vertical sound speed gradient.

When R is positive the sound waves are curved downward causing a slight sound amplification and when R is negative the sound waves are curved upward forming a shadow zone, where the sound attenuated. From Figure 3 one can see that for a typical day in Epidaurus, a temperature gradient exists from 09.00 to about 16.00 so that sound speed gradient dc/dh will vary from 0 to 0.15/s. This variation of gradient suggests a radius of curvature R from down to 2200 m, i.e. a shadow zone far exceeding the theatre area. Nevertheless, apart from average temperature fluctuations between orchestra and cavea extremes, the individual structural components of the theatre exhibit significant temperature fluctuations (see Figure 15). For the evening periods (Figure 15b) temperature in the cavea increased with the height. During the daytime (Figure 15a), temperature at the orchestra and the seating surfaces was higher.

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